Asia-Pacific J. Atmos. Sci., 47(4), 345-351, 2011
DOI:10.1007/s13143-011-0021-z

# Meteorological Responses to Mt. Baekdu Volcanic Eruption over East Asia in an Offline Global Climate-Chemistry Model: A Pilot Study

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(Manuscript received 22 April 2011; revised 10 May 2011; accepted 13 May 2011)


**Abstract:** We examine the meteorological responses due to the probable eruption of Mt. Baekdu using an off-line Climate-Chemistry model that is composed of the National Center for Atmospheric Research (NCAR) Climate Atmosphere Model version 3 (CAM3) and a global chemistry transport model (GEOS-Chem). Using the aerosol dataset from the GEOS-Chem driven by GEOS-5 meteorology, experiment and control simulations of the climate model are performed and their meteorological differences between the two simulations are analyzed. The magnitudes of volcanic eruption and column injection height were presumably set to 1/200 of the Mt. Pinatubo eruption and 9 km, respectively. Significant temperature drop in the lower troposphere (850 hPa), which is mainly due to a direct effect of prescribed volcanic aerosols from Mt. Baekdu, has been simulated up to about −4 K. The upper atmosphere (150 hPa) right above the volcano, however, shows significant warming due to the absorption of the infrared radiation by volcanic aerosols. As a result of the volcanic eruption in the climate model, wave-like patterns are shown in both the geopotential height and horizontal wind. The changes in the lower atmospheric temperature are well associated with the modification of the atmospheric circulation through the hydrostatic balance. In spite of limitations in our current simulations due to several underlying assumptions, our results could give a clue to understanding the meteorological impacts from Mt. Baekdu eruptions that are currently attracting considerable public attention.

**Key words:** Mt. Baekdu, volcanic eruption, meteorological response, climate model, chemistry-transport model

## 1. Introduction

Strong volcanic eruptions can cause significant perturbations to climate system by injecting large amounts of sulfur dioxide ($SO_2$) gas into the atmosphere. For example, after Mt. Pinatubo eruption of June 15, 1991, there were significant changes in the global temperature and atmospheric circulation for several years (Groisman, 1992; Hansen *et al*., 1992; Graf *et al*., 1993; Robock and Mao, 1995; Ramachandran *et al*., 2000).

Graf *et al*. (1993) conducted the perpetual General Circulation Model (GCM) simulation forced with perturbed aerosol and showed that the Mt. Pinatubo eruption caused the significant surface cooling over Greenland and North Africa/Middle East. Furthermore, their model also simulated stratospheric warming which led to the changes in the upper atmospheric circulation. Similar changes, i.e., tropospheric cooling and stratospheric warming, were also simulated in several models by the volcanic forcing (Free and Lanzante, 2009). Previous studies also indicate that the GCM model is very useful to investigate how the volcanic eruptions influence climate system.

Recently great public attention has been paid to Mt. Baekdu (128°03'E, 42°00'N; Fig. 1), since it is considered as the most dangerous and active volcano in East Asia. Mt. Baekdu erupted several times in recent 1000 years and the explosive eruption around 1000 AD is recognized as one of the two largest eruptions


**Fig. 1.** The location of Mt. Baekdu (closed circle). Historical record shows that Mt. Baekdu erupted in 969, 1668, 1702, and 1903 (Wei *et al*., 2003).

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on Earth in the past 2000 years (Horn and Schmincke, 2000; Wu *et al.*, 2009; Zou *et al*., 2010). The magnitude of the Millennium eruption was comparable to the 1815 eruption of Tambora in Indonesia (Sigurdsson and Carey, 1989). The Tambora eruption is believed to cause the most devastating volcanic winter in 1816 by releasing ~100 Mt aerosols, which became known as the "year without a summer" across the Northern Hemisphere (Stothers, 1984).

Mt. Baekdu volcano is one of the several volcanoes that might be related to the deep earthquake zone in the world and the substantial magmatic system has been located by measuring the earthquake activities (Wu *et al.*, 2005; Wu *et al.*, 2007; Wu *et al.*, 2009). Some signs of dangerous volcanic activity at Mt. Baekdu would be abnormal increases in minor trembling and surface temperature near Mt. Baekdu (Ji *et al*., 2010) and mountain height (Wu *et al.*, 2009). Because Mt. Baekdu is located on the border of China and Korea, explosive eruptions of Mt. Baekdu volcano, if any in the foreseeable future, would likely cause significant impacts on meteorology as well as catastrophic environment in East Asia including Korea, China, and Japan.

There have been many petrological and geochemical researches (Guo *et al*., 2006 and see their references). However, only a few studies have been performed on the climate effects of the volcanic eruption of Mt. Baekdu. For examples, Lie *et al.* (1996) and Wei *et al*. (1997) estimated that the next eruption of Mt. Baekdu might cause the Northern Hemispheric cooling by 0.85°C and 1.5°C, respectively. They used, however, simplified two dimensional energy balance models and their study is lack of the dynamical processes other than the direct effect of radiation. Therefore, a state-of-the-art climate model is required to properly simulate the volcanic-induced dynamical changes, along with a chemistry-transport model for spatio-temporal distributions of volcanic aerosols.

We here investigate effects of the possible eruption of Mt. Baekdu on regional meteorology in East Asia using the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3) with a 3-D global chemistry-transport model (Harvard GEOS-Chem).

## 2. Model simulations

The NCAR CAM3 (Collins *et al*., 2006) has been used in our study to simulate the perturbed meteorological fields and their related mechanisms due to the volcanic eruption of Mt. Baekdu. The NCAR CAM3 coupled to the Community Land Surface Model version 3 (CLM3) (Dickinson *et al*., 2006) uses the finite volume (FV) dynamical core in a horizontal resolution of 2° longitude × 2.5° latitude on 26 vertical levels. The ocean and ice are prescribed as an oceanic surface boundary condition, given as mid-month values of sea surface temperature (SST) as well as sea ice fractions. The SST and sea ice fractions are a time series of multi-year SST forcing data in horizontal grids of the CAM3, which is reconstructed with global HadISST data from the Met Office Hadley center (Rayner *et al.*, 2003). Therefore, our climate model setup is very similar to Youn *et al.* (2011).

Before the CAM3 simulations, the 3-dimensional (3-D) perturbed daily aerosol distributions due to an eruption of Mt. Baekdu are computed using a Harvard GEOS-Chem simulation driven by GEOS-5 assimilated meteorology from the NASA GMAO (Park *et al*., 2004) by adding volcanic $SO_2$ emission from Mt. Baekdu. The CAM3 code was slightly modified to utilize the daily aerosol data since the use of daily aerosols is appropriate for the proper inclusion of the aerosol effects on synoptic meteorology (Youn, *et al*., 2011).

Although it is hard to tell when and how strong Mt. Baekdu might erupt, Wei *et al*. (2003) suggested that the most probable magnitude of the next eruption of Mt. Baekdu could be in the range 0.1-0.5 $km^3$ of magma volume. The magnitude of volcanic $SO_2$ in the GEOS-Chem was set to be $1 \times 10^2$ kton (1/200 of the Pinatubo, Bluth *et al*., 1992) which is comparable to the magma volume of 0.1 $km^3$ (see Fig. 1 of Wallace (2001)). Assuming the maximum aerosol perturbations in the troposphere from the volcanic eruption although the height of eruption column will vary with eruption type, the plume height was set to be 9 km. In this study, the eruption of Mt. Baekdu was also assumed to begin in mid-June and lasts 20 days, which corresponds to the choice of meteorological fields used in the volcanic aerosol simulation. While the GEOS-Chem simulation begins on January 1, 2006, the assumed volcanic eruption starts from June 11, 2006. Since the choice of eruption timing is a bit arbitrary, more investigation is required into it.

The other GEOS-Chem simulation without Mt. Baekdu volcanic emissions was carried out to represent the climatological daily aerosol concentrations. Thereafter, the two daily aerosol data sets determined with and without Mt. Baekdu volcanic emissions, representing the volcano-perturbed and climatological aerosols, were provided into the climate model simulations (CAM3) as specified input. The prescribed daily aerosol data include sea salt, sulfate, soil dust, and black and organic carbons and are interpolated into the CAM3 during model integration, similar to the methodology in Youn *et al*. (2011).

We conducted sensitivity and control CAM3 simulations based on the perturbed and climatological daily aerosols. Except for the volcanic aerosol concentration shown in Fig. 2, both simulations are forced by the same conditions such as initial meteorological condition, fixed sea surface temperature and sea ice fractions. Therefore the differences between the sensitivity and control simulations are mainly due to the presence of the volcanic aerosols from Mt. Baekdu.

The sensitivity and control simulations with the CAM3 have 5 ensemble members, respectively. Although 5 ensemble members already allow the reliability of the simulation based on statistical significant test, we added 4 more ensembles of sensitivity simulations to show the meteorological signal induced by the volcanic eruption is significant. Each member of ensembles has slightly different initial meteorological conditions on different dates such as $1^{st}$ to $9^{th}$ of January 2006. In order to minimize the initial shock, the initial data are obtained from the 36 years (1970-2005) CAM3 spin-up integration forced by observed SST and sea ice (HadISST; Rayner *et al*., 2003). We analyzed the

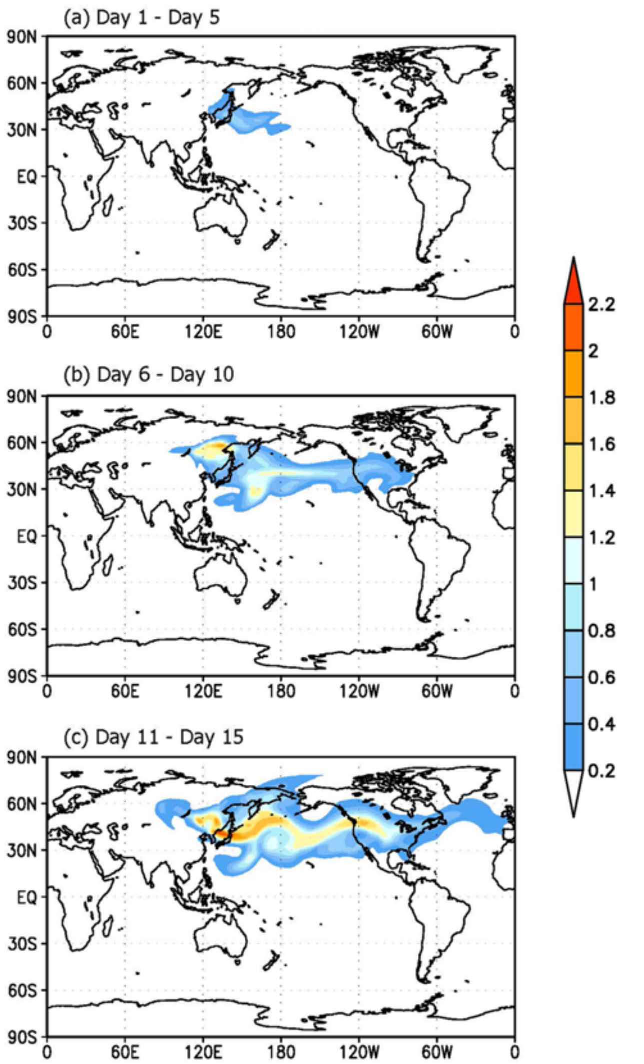


**Fig. 2.** Spatio-temporal distributions of the difference in column integrated sulfate aerosol ($\mu g\ m^{-2}$) between the two GEOS-Chem simulations with and without the Mt. Baekdu volcanic eruption for the first 15 days after the eruption.

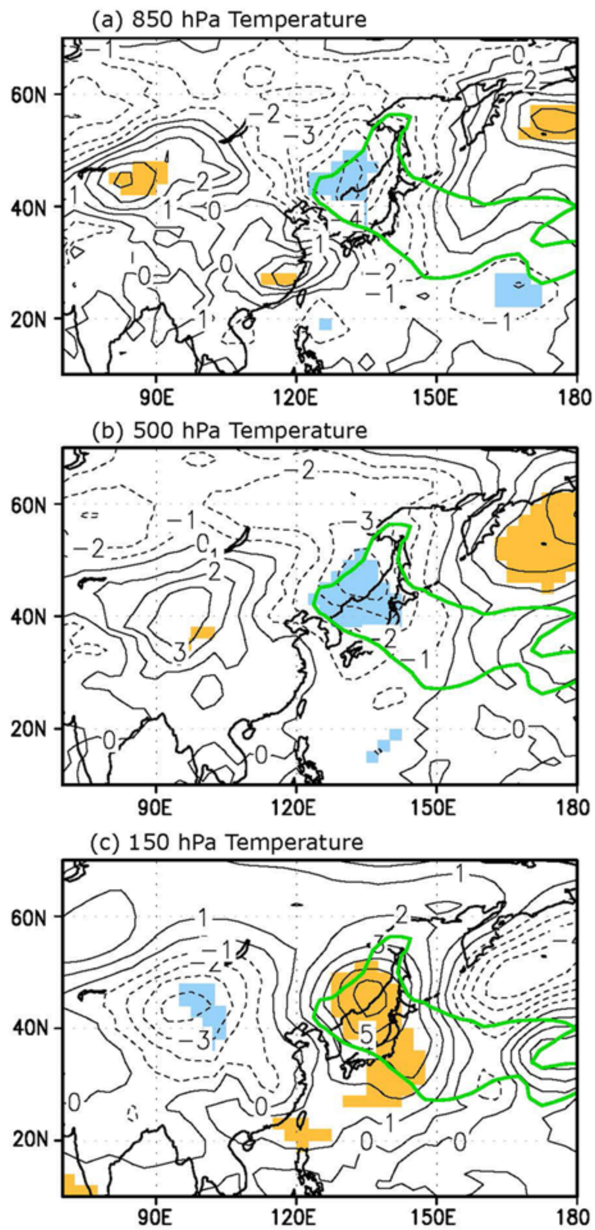


**Fig. 3.** Simulated changes of the air temperature of (a) 850 hPa, (b) 500 hPa, and (c) 150 hPa due to the eruption of Mt. Baekdu. Color shadings indicate statistically significant perturbations above 95% confidence level by t-test. The column integrated sulfate aerosol of 0.2 $\mu g\ m^{-2}$ is over plotted (thick solid line) for comparison.

meteorological changes during the first 5 days after the eruption by computing the differences between the two simulation results (sensitivity simulation minus control simulation). Coupled simulations using both the global climate model and the global chemistry transport model used in this study are already successfully applied to capture the meteorological changes due to Siberian fires (Youn *et al*., 2011).

## 3. Results

Figure 2 shows the changing spatial pattern of the difference in the total column sulfate aerosol simulated in the GEOS-Chem with and without the volcanic aerosol for the first 15 days after the eruption. The volcanic cloud moves eastward mainly during the first 5 days which is similar to what one would anticipate with the existence of the midlatitude westerlies. However, the cloud travels rather meridionally, even toward westward and almost reaches North Pole during day 11-15 (Fig. 2c). In addition, it takes about 3 weeks for volcanic cloud to go around the globe and come back to East Asia (not shown). The westward movement of the aerosol seems to be driven by the low level wind which reflects the circulation of East Asia summer Monsoon. Indeed, there were westerlies over the northern part of China and strong northward and eastward winds over the East China Sea during that time (not shown). The wave-like pattern of the sulfate aerosol shown in Fig. 2 is indicative of the transport of volcanic plumes due to the synoptic and planetary scale waves in the

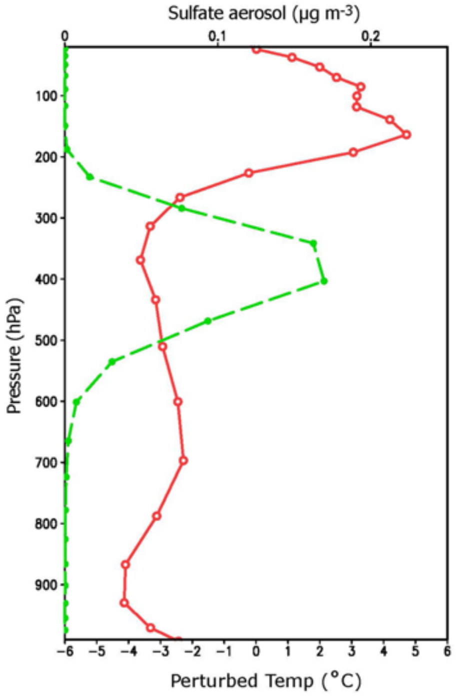


**Fig. 4.** Vertical distribution of sulfate aerosol (dashed, μg $m^{-3}$) and the perturbed air temperature (solid, °C) over the East Asia (120°E-150°E, 40°N-50°N) region.

midlatitude. The volcanic aerosol was mainly restricted to the Northern Hemisphere, which differs from the global spread of aerosols from tropical eruptions (Timmreck *et al*., 1999).

As discussed above, model results for the first 5 days after the eruption were analyzed to find initial meteorological responses in the East Asia due to the perturbed aerosol. Because the injected aerosol would be directly driven by wind during 16-25 days after the eruption or spreading in the Northern Hemisphere as time passes (not shown), it is difficult to estimate the changes in meteorology only over the East Asia due to Mt. Baekdu eruption after the first 5 days. The most previous works in this field have focused on the long-time, i.e., greater than several months, volcanic effects on climate (Andronova, *et al*., 1999; Yang and Schlesinger, 1999; Ramachandran *et al*., 2000; Graf and Timmreck, 2001; Timmreck and Graf, 2006). Among them, Graf and Timmreck (2001) simulated the zonal mean temperature changes with a GCM forced by an assumed mid-latitude eruption. Their results showed that the volcanic aerosol evenly restricted to the Northern Hemisphere leads to strong cooling in the Northern polar region.

Atmospheric temperature would be the most important variable to be analyzed to examine the effect of the volcanism. Figure 3 shows the perturbed temperature fields resulting from the eruption of Mt. Baekdu. The conventional understanding still holds such that volcanic cloud causes the atmospheric cooling by reducing the incoming shortwave radiation via a direct effect (Figs. 3a and 3b). In fact, negative temperature anomalies were found around Mt. Baekdu in the both lower (850 hPa) and middle (500 hPa) troposphere with a maximum decrease of about 4 K around 850 hPa. On the other hand, it is noteworthy that the anomalous warming over the China and North Pacific was resulted from the modification of atmospheric circulation (shown later in Fig. 6).

However, the upper atmosphere (150 hPa) shows significant warming around the volcano (Fig. 3c). Note that plume height in the GEOS-Chem model was assumed to be 9 km so that temperature change in Fig. 3c occurred above the bulk of the aerosol. The plume is distributed mainly over the upper troposphere

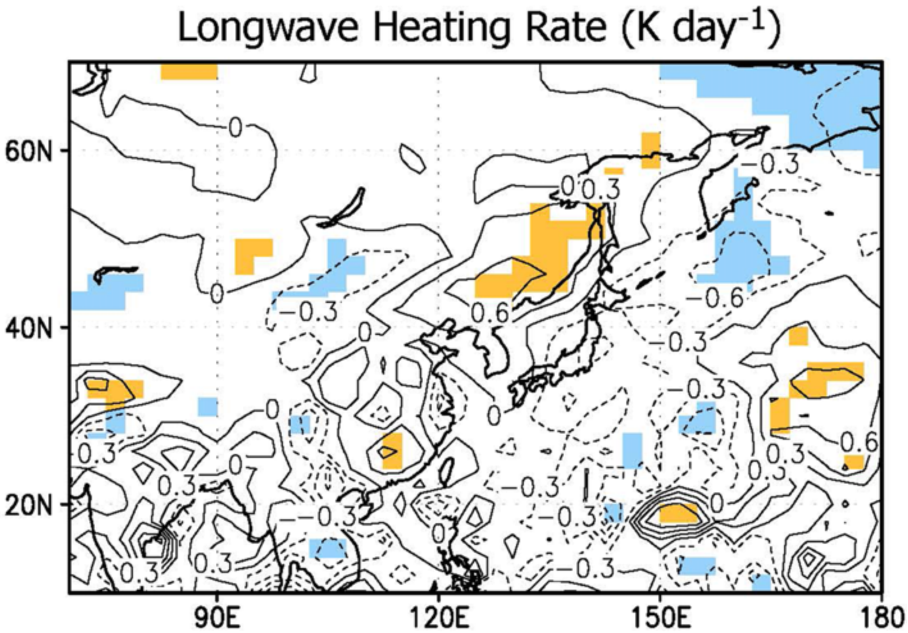


**Fig. 5.** Simulated changes in longwave heating rate (K $day^{-1}$) at the upper atmosphere (150 hPa). Color shadings indicate statistically significant perturbations above 95% confidence level by t-test.

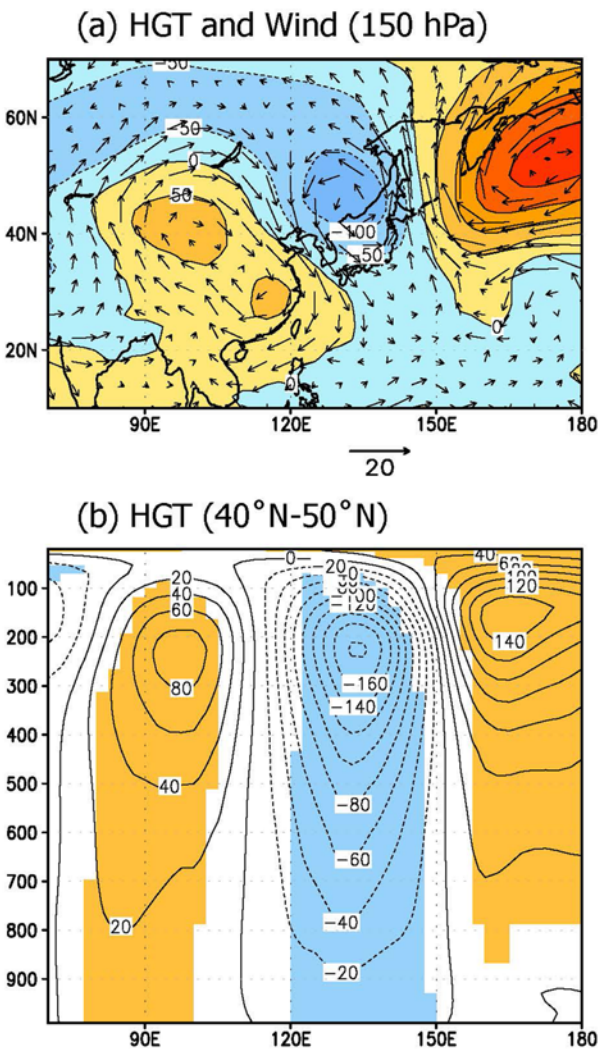


**Fig. 6.** Simulated changes in (a) geopotential height (m) in shaded contour and wind vector at the 150 hPa level and (b) vertical distribution of geopotential height meridionally averaged over the 40°N-50°N. In (b), color shading indicates statistically significant perturbations above 99% confidence level by t-test.

ranging between 600 hPa and 200 hPa with the centered around 350 hPa (Fig. 4). Figure 4 clearly shows the temperature increase above the aerosol cloud.

These patterns of tropospheric cooling and stratospheric warming in response to volcanic eruption are commonly captured in both observation and model studies (Graf *et al*., 1993; Timmreck and Graf, 2006; Free and Lanzante, 2009). The stratospheric heating at the top of the aerosol cloud shown in Fig. 3c may be due to the absorption of radiation in the near infrared. Robock (2000) and Stenchikov *et al*. (1998) suggested that this radiative warming effect dominates over the enhanced cooling due to the increased emissivity because of the presence of aerosols.

In order to confirm the importance of near-IR absorption in the stratospheric warming, the change in the longwave heating rate is shown in Fig. 5. The positive heating rate over the Mt. Baekdu is well consistent with the anomalous warm temperature at 150 hPa (Fig. 3c). This feature corresponds well with the results from the Robock (2000) and Stenchikov *et al*. (1998). In other words, the upper atmosphere around the Mt. Baekdu is warmed by absorption of near infrared radiation.

Interestingly, the changes in the longwave heating rate seem to impact on other regions too. For example, the upper atmospheric cooling in the both upstream and downstream region of Mt. Baekdu is well related to the negative sign of the longwave heating rate. This is indicative of the dynamical effect through changes in atmospheric circulation, since the upstream region (90°E-120°E, 40°N-50°N) is not directly affected by the volcanic aerosols.

Figure 6a shows the changes in the geopotential height and wind between the sensitivity and control simulations at the 150 hPa level. Over the bulk of the aerosol cloud, a notable cyclonic anomaly occurred both in the geopotential height and in the horizontal wind which is associated with the highly barotropic change in the geopotential height (Fig. 6b). This suggests that the radiative forcing due to the volcanic aerosol should produce a dynamical change or secondary circulation in the atmosphere. In other words, the decrease in temperature due to the scattering in solar radiation by aerosol leads to the decrease of geopotential height to satisfy the hydrostatic balance. This cooling effect in the troposphere (below 300 hPa) was strong enough to overcome the increase of geopotential height due to the longwave heating, which reconciles the barotropic change in geopotential height with the atmospheric warming at 150 hPa (not shown).

In addition, the height anomalies are also shown as a wavelike train with alternating anticyclonic and cyclonic circulations over the East Asia and North Pacific (Fig. 6a). The positive geopotential anomaly over the China and North Pacific may be responsible for the increase of temperature at 850 and 500 hPa (Figs. 3a and 3b), because of the hydrostatic balance between geopotential height and temperature. Therefore, the low-level temperature increases in these regions are resulted from the dynamical response to radiative effects of the volcanic aerosol.

It is well known that although volcanic eruption generally produces cooling at the surface in terms of the long-term global mean, there could be local and dynamical warming even in the surface (Robock, 2000; Stenchikov *et al*., 2002). For example, after Pinatubo eruption the winter of year 1991-1992 was warmer than normal over North America and the Eurasian. This surface changes were dynamically induced by the modification of large-scale atmospheric circulations through the significant warming in the equatorial stratosphere. Our model also exhibits an indirect and dynamical effect in the change of the lower troposphere through an anomalous synoptic wave-like pattern.

## 4. Summary and discussion

The sensitivity of the meteorological impacts of the possible eruption of Mt. Baekdu is investigated using the CAM3 simulations with and without the simulated volcanic aerosol from the GEOS-Chem model. The combined system of these two models, we call an off-line climate-chemistry model, can provide the reasonable estimation of what happens in the climate system over East Asia when the Mt. Baekdu erupts in foreseeable future. We analyzed the difference between sensitivity and control simulations of the CAM3 which were driven with volcano-perturbed and climatological aerosols from the GEOS-Chem, respectively. Time-lagged ensemble analyses with one-day lag length of initial conditions were applied to CAM3 simulations starting from January 1st to better assess volcanic impacts on meteorology in mid-June by showing the meteorological impacts is significant irrespective of the initial meteorology or model characteristics. The model setup is applicable for a longer integration of models such as seasonal prediction. However, this setup is valid for our study since what we focus is the differences in atmospheric phenomena induced by aerosol concentrations with and without volcanic eruptions. Validity of our modeling approach is partially shown by Youn *et al.* (2011) in a sense of avoiding difficulties in interpretation of the model results by natural climatic variability of a GCM. Compared to comparisons of one set of experiment and baseline simulations, the ensemble approach would thus be better applicable for our study of examining impacts of episodic but hazardous atmospheric phenomena.

When the amounts of volcanic cloud were to be 1/200 of that of Mt. Pinatubo on June 1991, our model simulations show that the temperature would decrease during the first 5 days after eruption by about 4 K at 850 hPa over the northern part of Korea Peninsular. This cooling is due to the reduction of incoming solar radiation through the absorption and scattering by the released aerosol from the volcano. However, the temperature of upper troposphere (150 hPa) above the bulk of aerosol significantly increases by 6 K. This warming is clearly induced by the enhanced absorption of the longwave radiation. Therefore, our modeling system confirmed the tropospheric cooling and stratospheric warming effects from the volcanic aerosol and showed the dynamical mechanism of the meteorological changes which would occur following the volcanic eruption.

Interestingly, there were also alternating cyclonic and anticyclonic wave-like patterns in geopotential height and wind over the East Asia and North Pacific regions, which were probably induced to satisfy the hydrostatic balance. This wave-like atmospheric response is responsible for the changes in temperature in the lower troposphere.

As far as we know, it is the first attempt to understand the direct meteorological responses due to the eruption of Mt. Baekdu, which attracts large attention by both the public and science society. However limitations in our work still remain due to inevitable assumptions, including the magnitude of the eruption, the plume injection height, season, and meteorological conditions. Further study is therefore needed. One more thing to be considered in a further study is that Mt. Baekdu has the caldera lake with a volume of 2 $km^3$ on the top. Therefore, the eruption of Mt. Baekdu would also release a large amount of water vapor into the atmosphere by the interaction between hot magma and lake water. Our model does not include this direct injection of water vapor. In spite of these limitations, we believe this modeling system we developed could be useful to predict the meteorological effect when the Mt. Baekdu is about to erupt.

***Acknowledgments.*** This work was supported by National Comprehensive Measures against Climate Change Program of Ministry of Environment, Republic of Korea (Grant 1700-1737-322-210-13). Daeok Youn was supported by Korea Environment Institute (GP2011-02-2). B.-K. Moon was supported by research funds of Chonbuk National University in 2010..

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